Ion Kinetics in the Solar Wind Generation Region

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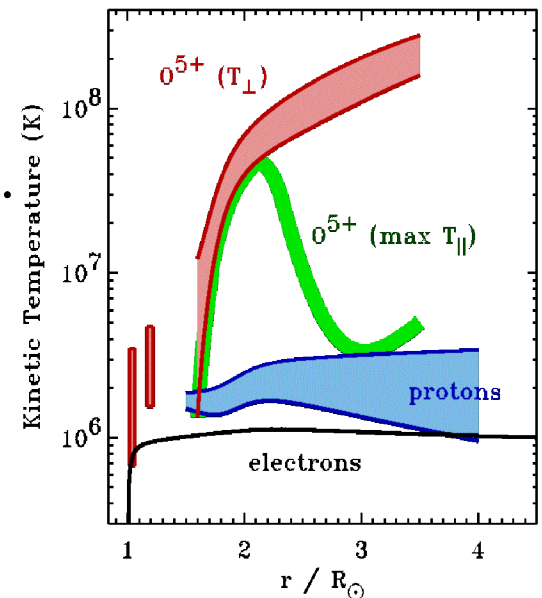
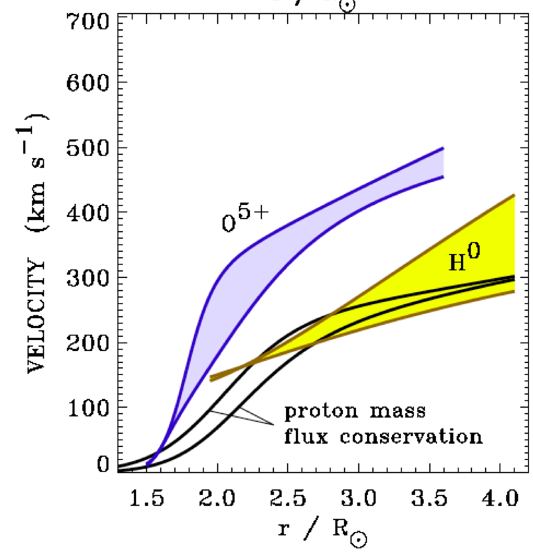
Observationally, most of what we know about the generation of the solar wind in coronal holes still comes from UVCS/SOHO measurements.





[Kohl et al., 98]

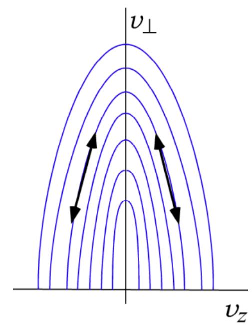
- Between $r \sim 1.5 - 6\ R_S$ we see strong perpendicular heating and acceleration of ions, with heavy ions (O^{5+}, Mg^{9+}, ...) energized more than protons.
- Heating is more fundamental, since acceleration can be supplied by the mirror force, along with the Alfvén wave pressure.
- Heating must be on kinetic scales to increase ion magnetic moment.

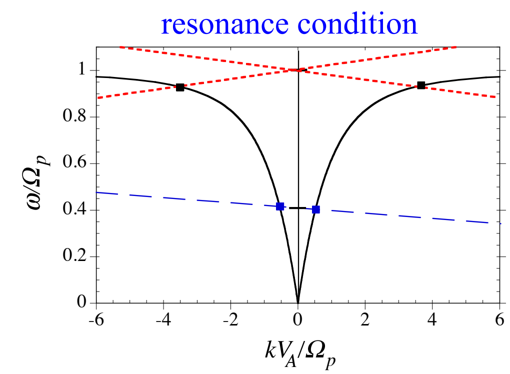
Can get power to kinetic scales through a turbulent cascade,

BUT we still do not know the specific heating mechanism.

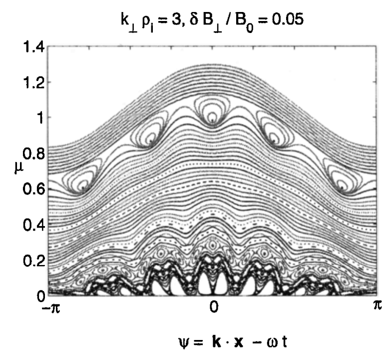
Primary hypotheses:

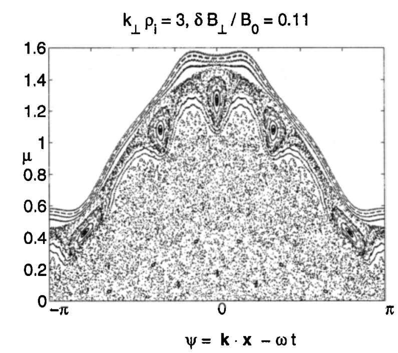
- Cyclotron resonant heating by quasi-parallel ion cyclotron waves. [Hollweg, Cranmer, Isenberg & Vasquez]



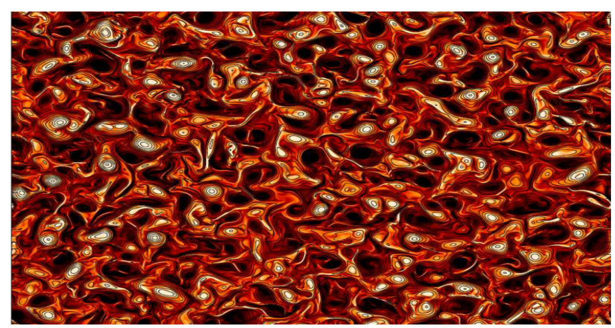


- Nonlinear stochastic heating by ion-scale perpendicular fluctuations. [Chandran, Voitenko & Goossens]





- Ion de-magnetization at turbulently-generated current sheets. [Matthaeus, Servidio, Osman]



What we DO know is that this

kinetic-scale heating takes place in conjunction with

other larger-scale forces that act on the

collisionless ion distributions in well-defined ways:

- Gravity
- Charge-separation electric field
- Wave pressure of Alfvén waves
- Mirror force in decreasing magnetic field

PLUS,

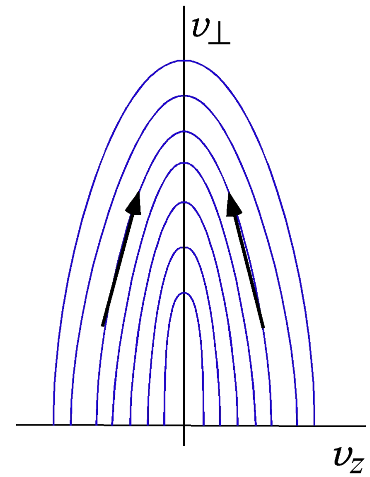
since time scale for resonant scattering << convective time scale

→ Ion distributions should be strongly organized by the

resonant cyclotron wave-particle interaction.

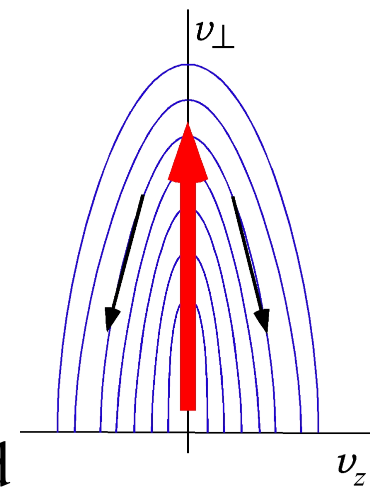
EITHER:

- Turbulent cascade of fluctuations to high $k_\perp$ yields sufficient 'leakage' (~ 1%) of power to high-frequency IC waves to heat the ions through resonant dissipation.



OR:

- Required perpendicular ion heating by other means creates anisotropic distributions which generate IC waves and scatter the ions.



Either way, the forces plus resonant scattering will yield proton distributions with characteristic features, due to the distinction between sunward and anti-sunward particles in the plasma frame.

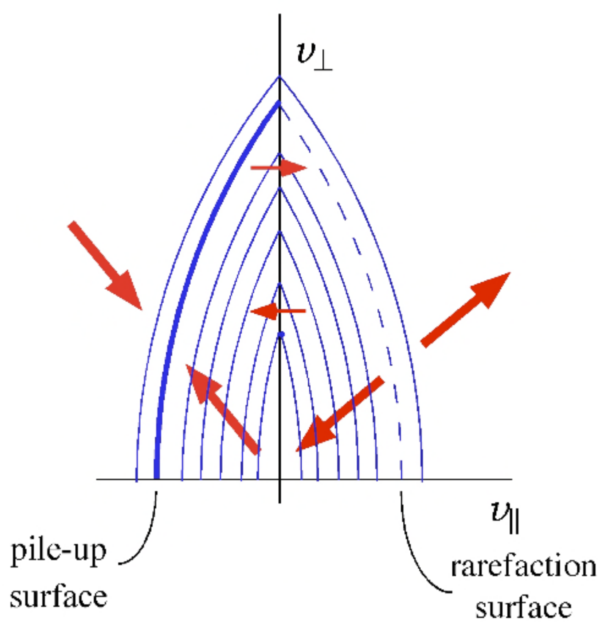
Note that: time scale for resonant scattering << convective time scale

Large-scale forces will effectively act on proton resonant shells,

as the scattering rapidly redistributes the particles.

- Gravity
- Charge-separation electric field } Net inward – indep. of v
- Wave pressure of Alfvén waves Outward – indep. of v

- Mirror force in decreasing magnetic field Outward – $\sim v_\perp^2$



We have modeled the radial evolution of coronal hole protons under these combined effects, for the case of ion cyclotron heating.

[Isenberg & Vasquez 2011, 2015]

Kinetic guiding-center equation

We obtain steady-state solution for proton distribution $f(r, \upsilon_z, \upsilon_\perp)$ in plasma frame flowing with radial bulk speed $U(r)$ in expanding field of radial coronal hole [area = $A(r)$].

Numerically, need to relax solution of time-dep eq to steady state:

$$\frac{\partial f}{\partial t} + \left(U + \upsilon_z\right)\frac{\partial f}{\partial r} + \left\{ -\frac{GM_s}{r^2} + \frac{e}{m}E(r) - (U + \upsilon_z)\frac{dU}{dr} \right\}\frac{\partial f}{\partial \upsilon_z}$$

advection gravity electric field inertial force

$$+ \frac{d}{dr}\left(\frac{<\delta B^2>}{8\pi}\right)\frac{\partial f}{\partial \upsilon_z} + \frac{\upsilon_\perp}{2}\frac{d \ln A}{dr}\left(\upsilon_\perp \frac{\partial f}{\partial \upsilon_z} - (U + \upsilon_z)\frac{\partial f}{\partial \upsilon_\perp}\right) = \left(\frac{\partial f}{\partial t}\right)_{w-p}$$

Wave pressure mirror force resonant diffusion

→ Protons are NOT test particles: U is self-consistent flow speed.

Taking

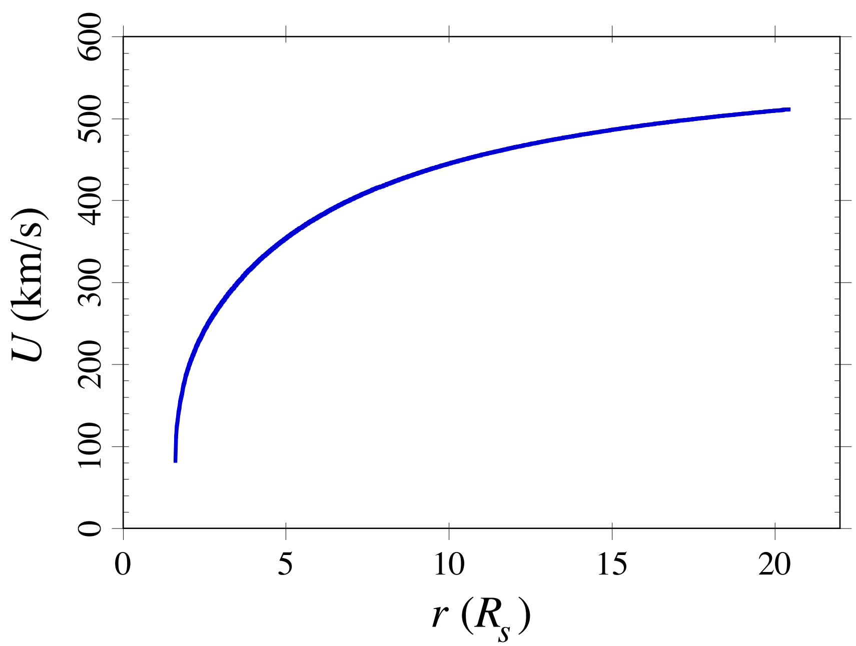
resonant wave intensity = 1% total modeled turbulent intensity

we get a reasonable fast solar wind.

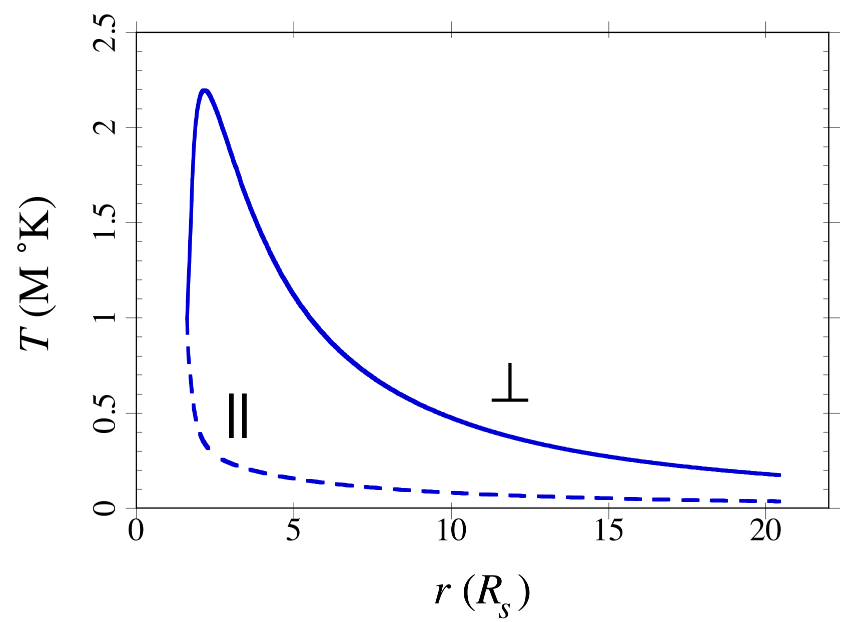
Moments of the proton distribution function show expected

acceleration and perpendicular heating.

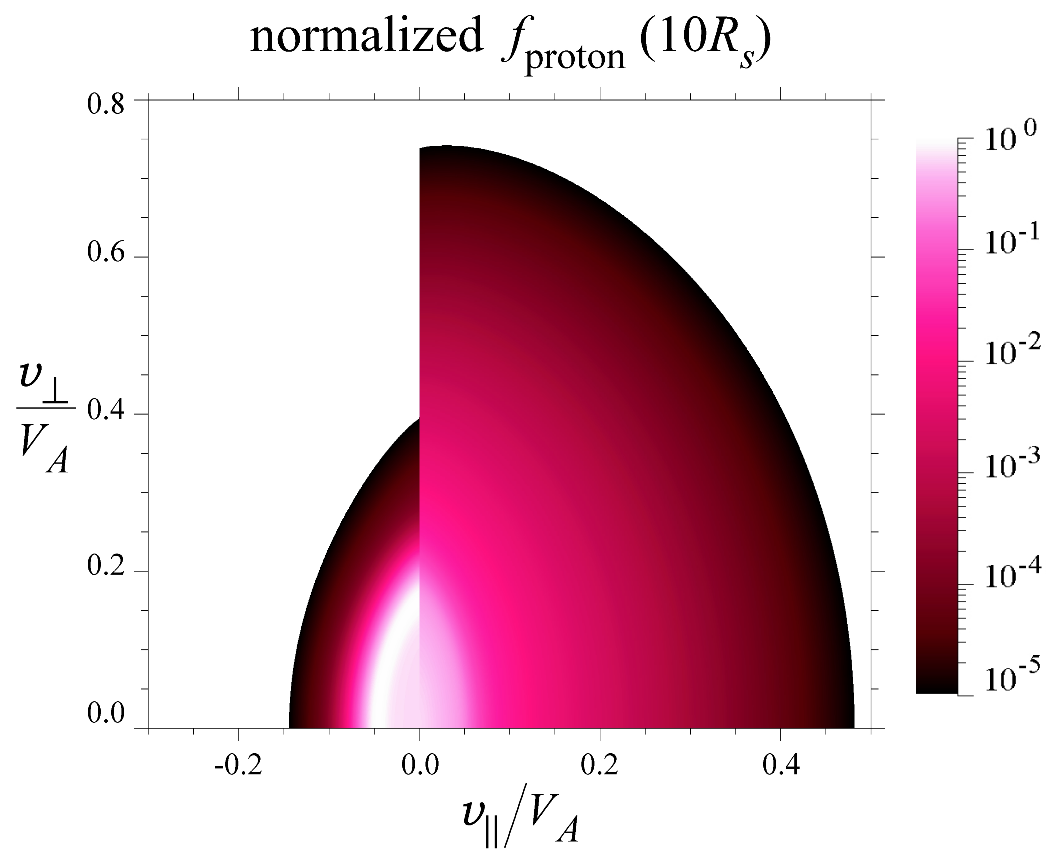
Speed

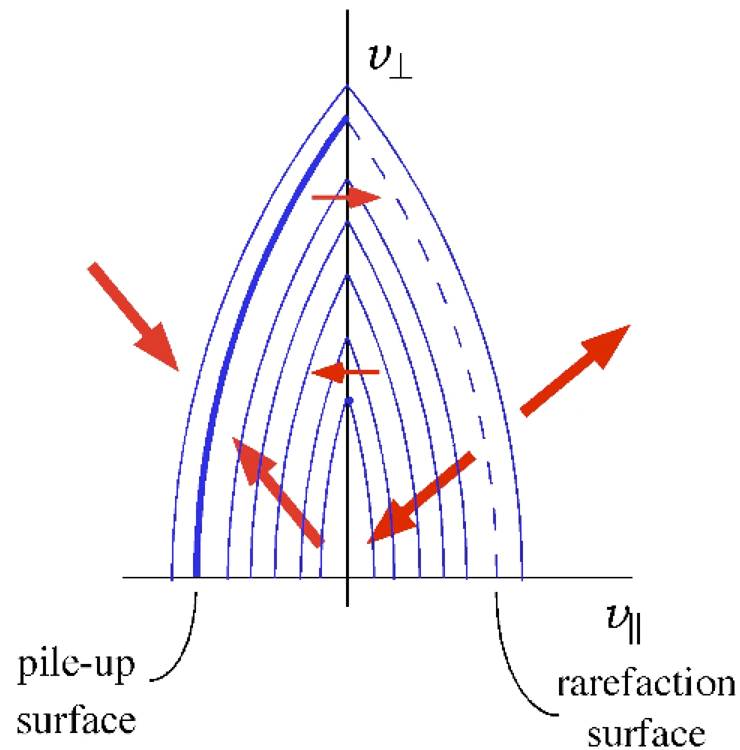


Temperatures



Proton distributions show predicted features:

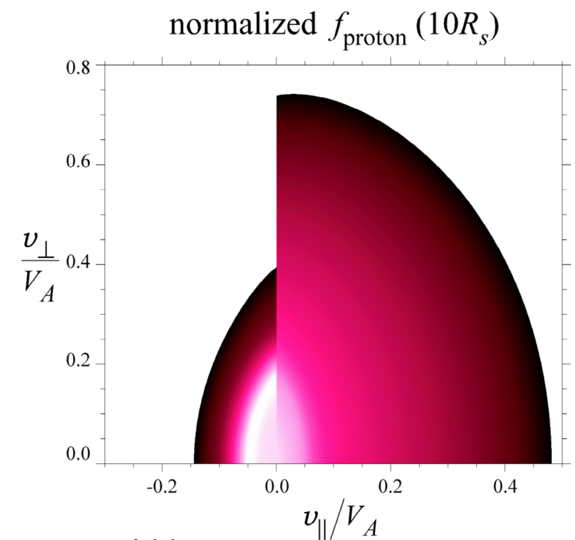




→ Strong asymmetry in proton rest frame:

- High-density compressional ridge on sunward side
- Expansion (heating) mostly on anti-sunward side

We note that:



- In-situ solar wind measurements ($r > 60\ R_s$) are asymmetric, though they do not show these specific features.

- We expect that measurements closer to the Sun will begin to display these characteristics as global forces and scattering rates will be higher.

- Solar Probe Plus & Solar Orbiter will observe the evolution toward these distributions, and provide clues on the processes which erode these features.

Conclusions

- Kinetic models of ions in the collisionless coronal hole are necessary to anticipate and correctly interpret future observations of near-Sun solar wind (Solar Orbiter & Solar Probe Plus).

- Resonant cyclotron ion scattering will strongly influence the kinetic evolution, no matter how the required perpendicular ion heating takes place.

- We will be testing this claim with models of the combined resonant scattering and global forces when driven by different kinetic heating mechanisms.

Resonant cyclotron wave-particle interaction

Standard quasilinear expression allowing for oblique waves [Stix, 92]

$$\left(\frac{\partial f}{\partial t}\right)_{w-p} = \frac{\pi q^2}{2m^2 \upsilon_\perp} \sum_{n=-\infty}^{\infty} \int d^3\mathbf{k}\, G\left[\upsilon_\perp \delta\left(\omega - k_z \upsilon_z - n\Omega\right) \left|\psi_n(\mathbf{k})\right|^2 G\, f\right]$$

where $$\left|\psi_n(\mathbf{k})\right|^2 = \left|\varepsilon_l J_{n-1} + \varepsilon_r J_{n+1} + \frac{\upsilon_z}{\upsilon_\perp} \varepsilon_z J_n\right|^2,$$

For the very low-β corona, we restrict the interaction to

- fundamental (n = 1) resonance only
- consider only EM ion-cyclotron waves, cold plasma dispersion

Double operation of $G \equiv \left(1 - \frac{k_z \upsilon_z}{\omega}\right) \frac{\partial}{\partial \upsilon_\perp} + \frac{k_z \upsilon_\perp}{\omega} \frac{\partial}{\partial \upsilon_z}$ yields

diffusion of protons in υ-space.

- Take steady 3D Kolmogorov spectrum $k^{-11/3}$,

  uniform in θ for $\theta_{\mathbf{kB}} < 60^\circ$.

- Radial profile of intensity scaled by

  Cranmer & van Ballegooijen [05] model for

  reflected and dissipated Alfvén waves.

- Flux tube has super-radial expansion factor $= 5$.

We artificially reduce the resonant spectrum with respect to large-scale amplitudes to represent the effect of inefficient turbulent transport to resonant scales.

- Taking the resonant intensities $I(r) = 0.01\, I_{\mathbf{CvB}}$

  gives $\sim$ correct heating rate/mass.